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Product Self-Management: Evolution in Recycling and Reuse

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This paper explores the potential to make product recycling and reuse easier by shifting responsibility for product management toward the product itself. Examples range from barcode-enabled Internet sales of used products to RFID-enabled garbage trucks that identify recyclable items and provide rebates. Initial steps toward product self-management have made opportunistic use of product bar codes and Internet markets. In the United States, Internet markets are driving increased reuse of products. In the European Union, recycling and waste management policy is driving the use of radio electronics in waste management. Prospects for product self-management are assessed from both a technological and an economic perspective. The technological analysis indicates that radio-frequency tags offer some advantages over bar codes, but their application to product self-management requires considerable investment in the waste management infrastructure. This suggests that early applications of advanced product tags are most suitable for Germany and other countries where the waste management industry has already integrated information technology into its operations. The economic analysis indicates that increased reuse of products can reduce consumption of new products and materials, although on a less than one-to-one basis, simultaneously reducing costs for consumers and deriving more value from existing products.

1. Concept of Product Self-Management

What is the future of environmental management of products? Will many more types of products be recycled? Will there be much greater use of second-hand products and parts? Will municipal waste management go high-tech? What will drive change?

The obstacles to product recycling and reuse are widely recognized. Products are widely dispersed among consumers, so finding and collecting products for recycling is difficult. Each consumer and business is faced with a complex problem of trying to optimize the management of many types of products. Moreover, there are many different models of some types of product, each requiring different end-of-life procedures.

This paper explores the proposition that product recycling and reuse could be made easier and cheaper by shifting responsibility for product management to the product itself. That is, a combination of information technology and product design could allow products to more or less automatically manage their end-of-life. Product self-management could include a wide variety of activities. It could include not only end-of-life management, which is emphasized in this paper, but also management of energy consumption and maintenance throughout the life of the product. For end-of-life, products could contain information on how they can be recycled, repaired, or sold. At a more developed level, products set out in the trash could sell themselves on the Internet or to scrap dealers. Consumers and businesses might automatically search the content of recycling bins and schedule delivery of items via a combined recycling/resale service. Optimistically, it is possible that waste flows would be reduced and that waste management would become profitable for consumers.

Presented as a pure concept, product self-management is an ideal that is unlikely to be realized. Under the guise of product self-management, it is possible to imagine a wide range of systems that would be expensive and unpopular. The actual development of product self-management will be constrained by costs; technology; public acceptance; and the economic, environmental, and social benefits. Environmentally motivated product self-management is only one aspect of a more general evolution toward the integration of information technology into everyday life (*1*). The purpose of this paper is to explore what is technically feasible and to begin to explore what might happen if products are set free to manage themselves.

2. Steps toward Product Self-Management

Although today's self-managing products are limited to those that biodegrade, there are some examples of steps toward product self-management for durable products. These include the resin identification codes for plastic bottles, use of product bar codes for recycling information, and developments in Internet markets. These are discussed in turn below.

Plastic Resin Identification Codes. It is widely recognized that labels on products can make recycling easier. For example, the 1988 development of the plastic resin identification codes enabled the widespread implementation of plastic bottle recycling programs (*2*). The labels on plastic bottles make it easier for consumers and recyclers to sort bottles for recycling, and in this sense, the plastic resin codes were an early step in the direction of product self-management.

Bar Codes for Recycling Information. Bar codes on products can provide more detailed recycling information. For example, as shown in Figure 1, bar codes on cell phones can be linked to web-based information for recyclers and dismantlers (*3*). Cell phones in Europe and many other countries use the GSM networking system, in which each phone is identified by a unique 15-digit number (the IMEI number). The first nine digits of this number identify the make and model of the phone. Most GSM cell phones have a label underneath the battery that contains the IMEI number both as a printed number and as a bar code. This IMEI number can be linked to a database showing how to dismantle each model of cell phone. This system was developed for use in the European Union where the recycling of cell phones and other electronic devices is expected to be mandated. This application depends on the fortuitous existence of a standard bar code on GSM cell phones that identify the make and model of the phone. No other electronic product is known to have a standard, cross-manufacturer label such as this.

Internet Markets. A progression toward product self-management can also be seen in the evolution of sales of second-hand goods on the Internet. On eBay, one of the most successful Internet businesses, people can auction off

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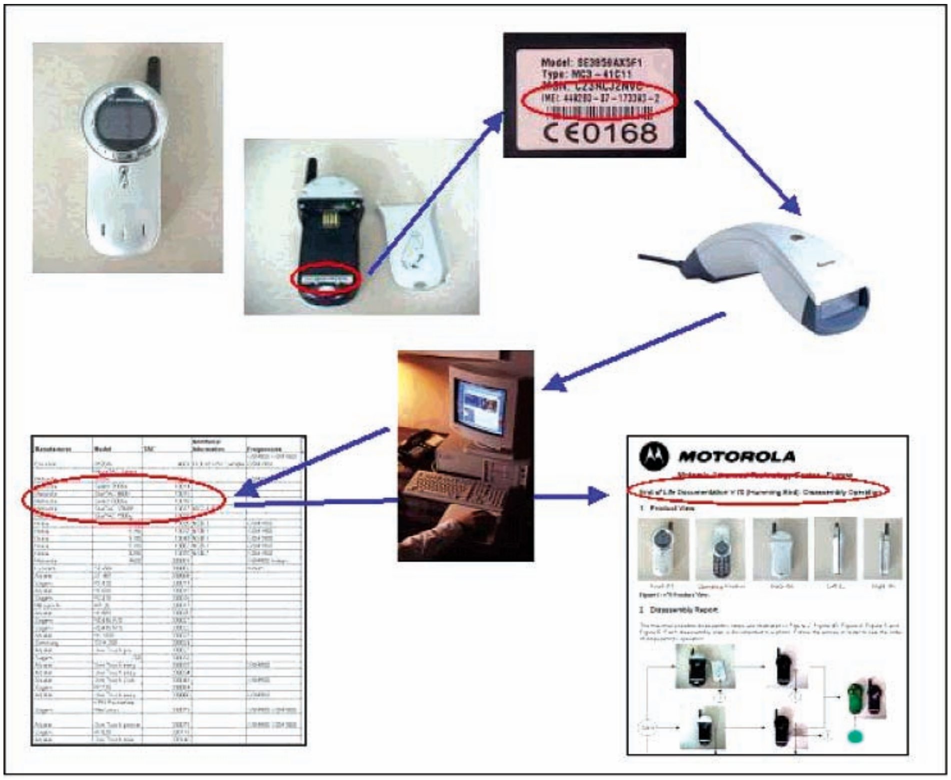

FIGURE 1. Bar code on product can link to web-based recycling information. A bar code inside the phone can be read by a bar code scanner as input to computer software that relates the bar code number to dismantlement information for the cell phone. Figure credit: M. Stutz, Motorola.

their used goods. To auction an item, sellers must type in a description, photograph the item, post it on the eBay web site, and pack and ship the item to the highest bidder after the auction is complete. The complexity of this procedure limits participation to a very small segment of consumers.

After the establishment of eBay, Half.com developed a simpler and more streamlined approach that solves some of the problems of eBay. Rather than having to photograph and type in a description of the item, users of Half.com can simply type in the item's UPC code (or, for books, the ISBN code), and the Half.com database brings up a product description and photograph. This works well for books, videos, computer games, and CDs because they typically have a bar code UPC or ISBN label; the system also works if the user types in the title of the item. (Not incidentally, Half.com has now been bought by eBay.)

The Half.com innovation has established the use of product bar codes for end-of-life management. Although the goal of Half.com's developer was to make it easier to sell an item than to throw it away (*4*), Half.com is still far from a "product self-management system", because sellers still have to pack and ship their goods after they are sold. Packaging and mailing adds considerably to the expense and inconvenience of consumer-to-consumer Internet markets such as eBay and Half.com and limits them to easily mailable products. Development of more localized systems could reduce the packaging and mailing burden and could provide opportunities for the development of new second-hand markets.

In comparing these three examples of steps toward product self-management, it is worth noting that the plastic resin codes were implemented by the plastics industry specifically to make recycling easier. In contrast, both the cell phone recycling example and the Half.com example show the opportunistic use of bar codes on existing products. Plastic bottles are short-lived products; product manufacture and recycling can be implemented essentially simultaneously. The longer lived the product, the greater the difficulty of planning for future recycling. Opportunistic use of bar codes and Internet-based databases can support recycling and reuse of older products now and can provide flexibility for recycling and reusing today's products many years from now.

A key feature of these opportunistic uses of bar codes is that the bar code only needs to contain the make and model of the product. The information relevant to recycling and reuse is linked to these barcodes but is stored elsewhere, on computers, and is developed as needed.

It is also worth noting that the cell phone recycling example is from Europe, where there is policy emphasis on product recycling. The Internet market example is from the United States, where there is less policy emphasis on product recycling and more consumer interest in selling items on the Internet.

3. Advances beyond Bar Codes

One way to think about the potential development of product self-management is to consider the capabilities of technologies. While it is likely that the continued development of the Internet will shape the development of product self-management, the technology for identifying products might take a number of forms. In each of the early examples discussed above, a label is used to identify the product. In each case, a person has to pick up the item and either read the label or scan or type it into a computer.

Technologies to identify products automatically and at a distance could reduce the need for human intervention. Although there are several ways to do this, radio-frequency identification (RFID) tags have received considerable attention as a potential replacement for ordinary bar codes (*5*). Radio-frequency tags, effectively electronic bar codes, can be read automatically; they can store more data than a UPC code, and some can be updated.

Understanding the basic physics of RFID systems can provide a basis for evaluating whether and how RFID might

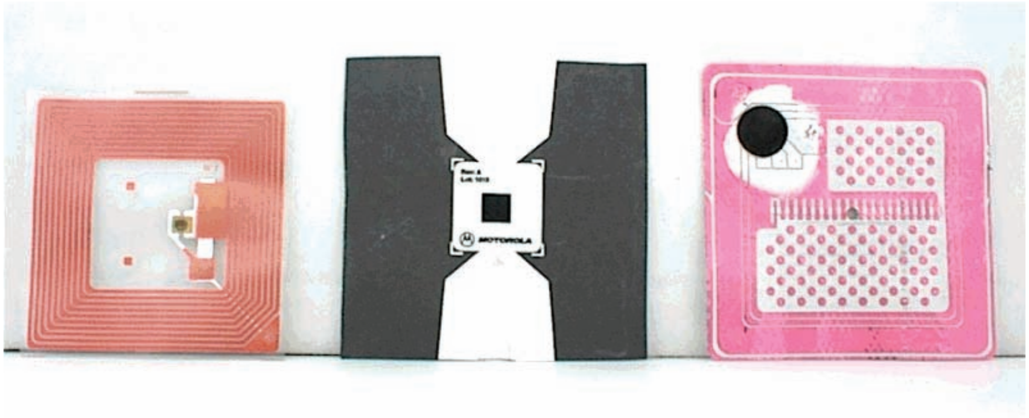

FIGURE 2. Selection of RFID tags. The tags on the left and right are inductive RFID tags such as are discussed here. The tag in the middle is a capacitive RFID tag with similar capabilities. From ref *6.* Photo credit: S. Saar. Reproduced by permission of MIT Press.

be effective in product self-management. Most RFID tag systems consist of an antenna, a tag, and a reader (*7*). The antenna is typically in the shape of a loop; a radio signal from the antenna loop powers the tag. The tag typically contains a set of aluminum or copper loops. The current in the antenna loop induces a current in the tag loops in a straightforward realization of Faraday's law (*8*). The tag is designed to resonate at the frequency of the radio signal being sent by the antenna. A microchip on the tag modulates the resonant signal, which is received and decoded by the system reader.

To make the physics simple, the antenna will be assumed to be circular; by the Biot−Savart law, the magnitude of the magnetic field produced by a circular loop antenna at a distance r from the antenna is

$$B = \frac{\mu_0 N I a^2}{2(a^2 + r^2)^{3/2}} \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Vs/mA is the permeability of free space, I is the current through the antenna loop, N is the number of turns in the antenna loop, a is the radius of the antenna loop, and r is the perpendicular distance from the center of the antenna.

By Faraday's law, the voltage (V) induced in the tag loop is

$$V = -N_t \frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{S} \tag{2}$$

where N_t is the number of loops in the tag and the surface integral is over the area of the tag loops. The minimum voltage required to turn on the CMOS chip on the tag is currently about 1 V (*9*). Based on this minimum voltage, the maximum read range (r_{max}) can be derived from eqs 1 and 2:

$$a^2 + r_{max}^2 = (\pi \mu_0 f A I N N_t a^2 / V)^{2/3} \tag{3}$$

where A is the area of the tag and f is the frequency of the radiation. In a typical RFID system, the current is about 100 mA, and the frequency (f) is 13.56 MHz. Figure 2 shows a tag on the left with nine copper loops ($N_t = 9$) and an average loop area of 10 cm^2. Taking the antenna to have 1 turn ($N = 1$) and the radius (a) of the antenna loop to be 10 cm, r_{max} is 13 cm.

It is clearly possible to achieve a read range greater than 13 cm by increasing the value of some of the parameters. But eq 3 shows that the dependence of the range on all the circuit variables goes basically as the one-third power. This means that a 3 order of magnitude improvement in circuit performance is needed to achieve a 1 order of magnitude improvement in RFID range. It is also straightforward to show that the magnetic field of the antenna reaches a maximum at $a = r$. This suggests that the read range is not likely to much exceed the dimensions of the antenna. For the near future, read ranges of RFID circuits can be expected to be less than 1 m.

Range is not the only limitation of RFID systems. Because RFID operates with electromagnetic fields, metal interferes with the signal. If the tag is surrounded by metal, the signal will be blocked; if the tag is placed directly on metal, it will not work, and if the tag is placed near metal, it can be detuned. If the tag is designed to be placed on a metal-containing object, the tag capacitance or inductance can be modified accordingly. But if the tag needs to be read in a variety of situations, such as in a trash can or recycling bin, then the presence of metal can be a significant problem.

Lower frequency systems work better near metal. For this reason, a number of electronic theft detection systems operate in the kiloHertz range. But as indicated in eq 3, lower frequency systems have a shorter range.

These physical limitations indicate that to read an RFID tag on a product, the reader needs to be closer than 1 m and that the amount of metal nearby needs to be limited. This rules out using RFID to identify an entire truck full of products or an entire room full of items. However, if the amount of metal is limited and if the antenna is well designed, RFID technology could read the entire contents of a standard large trash can.

Trash cans are, in fact, an early application of RFID tags. In Europe, households are often charged by the mass of waste disposed. To simplify data management for the weighing of trash cans during curbside residential waste collection, RFID-enabled garbage collection is widely used. Garbage trucks are outfitted with a scale to weigh the garbage can, and the household is identified through an RFID tag on the garbage can. An RFID antenna and reader on the truck reads the tag on the trash can when the can is placed on the truck's scale. In Germany, 20% of garbage collection is managed with such RFID systems (*10*). In the United States, where there is less policy emphasis on reducing the amount of municipal solid waste, there are currently no such weight-based "pay as you throw" municipal waste collection systems that charge by the weight of garbage disposed. A recent study in the United States concluded that an RFID-enabled weight-based pay-as-you-throw system would cost an additional \$1−2/month per household; the study also reported that pay-as-you-throw systems in Europe have resulted in significant increases in household recycling rates (*11*).

These garbage-weighing systems could be implemented with either RFID tags or with bar codes. The essence of the innovation is not the technology of the label but rather the general ability of a computer associated with the garbage truck to receive information from an individual's garbage can.

RFID-enabled garbage weighing is not a product self-management system, but it could provide the infrastructure for its development. Beyond simply measuring the mass of material disposed, these systems could also identify specific items being disposed if the items had RFID tags on them. RFID tags on products could be read by garbage or recycling trucks at the same time that the main can tag is being read. Using such a configuration, the collection service could, for example, provide rebates for recycling of items (*12*).

Given the broad interest in the European Union in product recycling, it is conceivable that use of RFID tags on recyclable products might be mandated to facilitate recycling or that manufacturers might put RFID tags on their products in order to manage rebates for recycling.

Progress from simply weighing the mass of garbage to identifying specific products in garbage would be a small step toward product self-management. An even bigger step would be to have the RFID antenna and reader on the trash can rather than on the truck. A product reader located on the trash can could read the item as soon as it was deposited. In such a system, recycling bins could relay their contents to a central system as soon as they are put out by the householder. This would allow several hours for scrap dealers and Internet-based sales services to remove items of value before the general pickup. The obstacles to such an arrangement are the high cost of installing a reader on each trash can as well as the cost and difficulty of setting up a network to collect and manage the information received from the trash cans.

4. Effects of Product Labeling on Reuse of Products

Another way to think about the development of product self-management is to consider the environmental implications. While the environmental implications of recycling are well studied, reuse has not yet been as deeply examined. As the Half.com example indicates, the trajectory of product self-management in the United States is encouraging increased reuse of products. It could be useful to understand the environmental implications of such a development.

While environmental engineers and regulators may want to promote both recycling and reuse, manufacturers may fear that greater reuse of their products would reduce their sales. On the other hand, skeptical regulators may ask if greater reuse of products will simply result in consumers being able to buy more products cheaply, with little environmental benefit.

Indeed, there are cases in which buying a new product has less environmental impact than buying used. A key example is the refrigerator because chlorofluorocarbon (CFC) refrigerants have been banned and average refrigerator energy consumption has been reduced by about two-thirds over the past 25 yr (*13*). Moreover, the environmental impact of packaging and delivery of a used product, for example, from an individual selling on eBay, can be significant (*14*, *15*).

For many products, however, environmentalists assume that reuse is environmentally beneficial because it replaces the manufacture and purchase of new goods. Manufacturers may oppose this type of reuse for the same reasons. There is a rich economics literature on planned obsolescence, the incentives of producers to alter the durability of their products, and the circumstances that promote or inhibit second-hand markets. The idea that producers might want to decrease the durability of their goods in order to induce consumers to replace their goods more frequently is consistent with the idea that reuse of products reduces demand for new products. Factors that affect the reuse of products extend beyond durability per se and include manufacturer practices with respect to product maintenance, access to spare parts, software upgrades and compatibility, and copyright protection (*16*).

As second-hand markets have developed, manufacturers of a number of types of new goods have claimed that their sales are being hurt. The recording industry has claimed that sales of used CDs hurt sales of new CDs (*17*). The book industry has claimed that sales of used books on the Internet hurts sales of new books (*18*). Many countries ban the import of used cars in order to protect domestic producers of new cars (*19*).

A basic understanding of the impact of second-hand sales on the sales of new goods can be developed through an economic model of second-hand markets (*20*). In a simplified version, consumers can be assumed to buy new, used, or not at all. The price for a new product is p_N. The used price is p_S. The value of the service provided by a used product is v, and the value provided by a new product is $v + k$, where k is the extra benefit of newness. Consumers have different valuations of these services according to a parameter θ that is between zero and one, with higher θ denoting individuals with higher willingness to pay.

The options available to the consumer are to buy new, used, or not at all. The utility V a consumer derives under each of these options, respectively, is

$$V_N = (v + k)\theta - p_N \tag{4}$$

$$V_U = v\theta - p_S \tag{5}$$

$$V_Z = 0 \tag{6}$$

In this particular model, the consumer who buys new simply gives away or throws away his goods, and the price of second-hand goods is set exogenously. More complex models of this type, in which the buyer of new goods sells his goods used and in which the second-hand price is determined endogenously, have been developed (*20*). Such models can explicitly include transaction costs and can explore the effect of changes in product lifetime and transaction costs on material consumption (*21*). However, this very simple model is used here, not only to provide a straightforward calculation but also because in many newly developing second-hand markets, second-hand prices are largely exogenous and the buyer of new goods does give away his used goods essentially for free (to charity rummage sales, for example) rather than selling them used. In the book market, for example, most books are bought new, and most people who buy used books are not also sellers of used books. Even on the Internet, the price of used books is determined largely by professional book dealers who post their stock on the Internet rather than by individual book owners who sell their books after reading them.

The basic assumption of the model is that consumers will choose the utility-maximizing option. The point of indifference between buying new and used, defined by setting $V_N = V_U$, is

$$\theta_{NU} = (p_N - p_S)/k \tag{7}$$

Likewise, the point of indifference between buying used and not buying is

$$\theta_{UZ} = p_S/v \tag{8}$$

The consumers buying new are those with θ greater than θ_{NU}, those buying used are those with θ between θ_{NU} and θ_{UZ}, and those not buying are those with θ less than θ_{UZ}. Assuming, for simplicity, that consumers are uniformly distributed on θ, eqs 9−11 show the fraction of consumers buying new, used, and not at all, respectively:

$$N = 1 - \theta_{NU} = 1 - (p_N - p_S)/k \tag{9}$$

$$U = \theta_{NU} - \theta_{UZ} = (p_N - p_S)/k - p_S/v \tag{10}$$

$$Z = p_S/v \tag{11}$$

When the second-hand price changes, the changes in N, U, and Z are

$$\frac{dN}{dp_S} = \frac{1}{k} \tag{12}$$

$$\frac{dU}{dp_S} = -\frac{1}{k} - \frac{1}{v} \tag{13}$$

$$\frac{dZ}{dp_S} = \frac{1}{v} \tag{14}$$

Using the chain rule, when the number of used sales changes and other variables are fixed, the change in the number of new buyers and nonbuyers is, respectively:

$$\frac{dN}{dU} = \left(\frac{dN}{dp_S}\right)\left(\frac{dU}{dp_S}\right)^{-1} = \frac{-v}{v+k} \tag{15}$$

$$\frac{dZ}{dU} = \left(\frac{dZ}{dp_S}\right)\left(\frac{dU}{dp_S}\right)^{-1} = \frac{-k}{v+k} \tag{16}$$

The fact that dN/dU is negative and less than one shows that, when the second-hand market increases, the market for new goods always decreases but by an amount less than one. Some of the used sales come from people who would have bought new, and some of the used sales come from people who previously would not have bought. When the value of newness is relatively small (that is, when $v \gg k$), eq 15 shows that an increase in used goods sales can result in a loss of sales of new goods on an almost one-to-one basis. However, when the value of newness is high ($v \ll k$), eqs 15 and 16 show that an increase in used goods sales has little affect on the market for new goods because the buyers of the used goods are primarily those consumers (Z) who would not have bought new.

Quantitative understanding of the impact of used goods markets on the consumption of materials and consequent environmental impacts will require detailed analysis beyond the level of this simple model. What the simple model shows, however, is that the reuse of products can have quite different economic and environmental effects than the recycling of products and that these effects can be quantitatively assessed.

The overall environmental impact of a second-hand market will depend both on the extent to which second-hand sales replace the sale of new goods, as in eq 15, as well as on the overall size of the second-hand market. Internet markets are still small, representing only a few percent of the traditional markets. But there are second-hand markets that are larger than the corresponding market for new goods, with the car market being an obvious example. It is possible that the second-hand markets for many other products will also become as large or larger than the corresponding market for new goods.

5. Discussion: Promoting the Development of Product Self-Management

In the United States, market developments and Internet technologies are driving changes in product end-of-life management. In the European Union, in contrast, product end-of-life management is being driven by waste and recycling policy. As a result of these differences, the trajectories toward product self-management are somewhat different in the United States than in the European Union.

A market-driven approach to product self-management, that builds on innovations in Internet markets, can drive increased reuse of products. Growth of second-hand markets can make material consumption more efficient and can benefit consumers by providing wider access to products at lower prices.

A recycling-driven approach to product self-management, that builds on policy requiring product recycling and waste stream reduction, can drive increases in recycling but may not necessarily be accompanied by increases in product reuse. To go beyond bar codes to technologies such as RFID tags could require both an infrastructure of RFID readers in the waste management system and policies mandating product recycling or waste reduction. These conditions are largely met in the European Union.

Product manufacturers and engineers could encourage product self-management by putting permanent, standard identifiers (such as the UPC code) on every product and by linking product information, such as owners manuals and recycling information, to the product identifier. This would, in a sense, amount to a social and economic experiment to observe over time the co-development of recycling, reuse, and information technology.

Both because there could be significant economic implications of product self-management and because standardization is important, discussions across industries and with environmental regulators could be helpful. Developing a broad consensus on the potential benefits and impacts of product self-management and on the effectiveness of various approaches could provide a framework for standardized and compatible steps to promote product self-management.

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